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Engineering *Ulysses* Extended Mission

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Abstract

The *Ulysses* Mission is a collaboration between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). The mission is unique, enabling exploration of the heliosphere within a few astronomical units of the Sun over a full range of heliographic latitudes - adding a third dimension to our understanding of the Solar System.

The advanced scientific instrumentation on *Ulysses* continually measures the properties of the heliospheric magnetic field, the solar wind, solar radio bursts and plasma waves, galactic cosmic rays, energetic particles, solar X-rays, and interstellar neutral gas. By the end of 1995, the spacecraft will have completed measurements at heliographic latitudes up to 80 degrees over a single orbit of the Sun. The properties of the heliosphere are solar cycle dependent, and *Ulysses* first orbit of the Sun will have taken place around a solar minimum. In order to characterize the heliosphere over a full (11 year) solar cycle, it is desirable to continue measurements over a second orbit of the Sun, a new Odyssey that will extend through 2001. Since the spacecraft was only designed for a five-year mission, a number of technical challenges have been surmounted in order to demonstrate the engineering feasibility of this unparalleled scientific opportunity.

This paper describes the changes that were necessary to the *Ulysses* mission engineering and mission operations in order to ensure continual, effective payload operation throughout 1996-2001.

The Mission

Ulysses was launched in October 1990 on the space shuttle *Discovery*. Following deployment, the spacecraft was accelerated by an IUS and PAM-S

into an in-ecliptic transfer trajectory to Jupiter. A gravity assist flyby was necessary at Jupiter in order to produce *Ulysses*' inclined, heliospheric trajectory as depicted in figure 1.

The primary objective of the *Ulysses* mission is to characterize the heliosphere over the full range of solar latitudes. The spacecraft carries instrumentation¹ to perform measurements of the interplanetary magnetic field, solar wind plasma, radio and plasma waves, energetic particles, cosmic ray isotopes, interstellar neutral gas, and interplanetary dust. Full descriptions of the instruments and scientific objectives of the mission² are not included here, but are thoroughly treated in the above referenced publications.

The spacecraft³ is spin-stabilized, with a High Gain Antenna (HGA) mounted with its boresight along the spin axis. Because the spacecraft is not subject to large perturbing forces, it maintains a stable inertial attitude for long periods of time. Attitude maneuvers are necessary to compensate for apparent Earth drift, keeping the HGA pointed within about 1° of the Earth. The precise magnitude of the allowable offpointing depends on the link budget for a given mission phase. Attitude control is provided by catalytic decomposition thrusters fueled by hydrazine.

Ulysses has both X and S-band transmission capability, but X-band only is used to maintain the downlink via the HGA. The spacecraft also has front and rear S-band quadifilar helix type low gain antennas (LGAs); S-band transmission was provided for use during the launch and early mission, and is only used now during limited periods of Radio Science investigation.

The spacecraft is powered by a Radioisotope Thermoelectric Generator (RTG)^{4,5}, providing about

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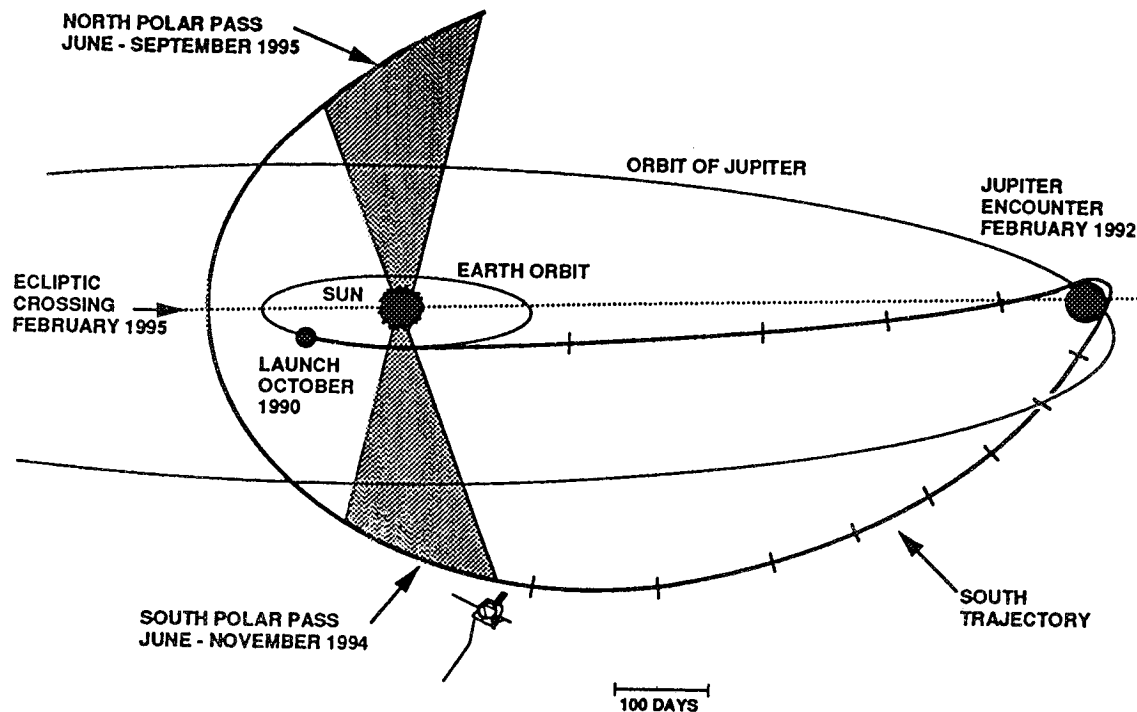
287W at beginning of mission. Solar heating varies from 1500W/m^2 at beginning of mission to about 45W/m^2 at aphelion; such large variations in environmental conditions make thermal control and power management of particular importance. Power not consumed by operational units and heaters is dumped to resistances inside the spacecraft to contribute to general heating. This power can be diverted to resistances outside the spacecraft when the interior becomes too warm. Dissipation is shifted between dedicated heaters, internal power dumpers (IPDs) and external power dumpers (EPDs) to achieve the optimal thermal state for the spacecraft.

reconfiguration from anomalous modes, and carry out on-board data processing.

The spacecraft is operated by a joint ESA/NASA team situated at Jet Propulsion Laboratory in Pasadena, California.

Ulysses at Solar Maximum

The basic properties of the heliosphere are solar cycle dependent. *Ulysses* southern polar pass and upcoming northern polar pass will take place at solar minimum, the equivalent passes in 2000 and 2001



The spacecraft Data Handling Subsystem (DHS) performs the usual functions of acquiring, decoding and accepting incoming commands and distributing these commands to the instruments and platform subsystems. Only 40 commands can be stored as a 'sequence' on-board, so a significant amount of commanding in near-real-time. All telemetry acquisition and processing is performed by the DHS, with data storage on two redundant 45Mbit tape recorders.

The DHS incorporates a software package tailored to *Ulysses*, with applications that monitor spacecraft health and safety, initiate recovery and

will take place at solar maximum. The extended mission will enable characterization of the heliosphere not only over all latitudes, but over the full 11 year solar cycle, greatly enhancing the scientific return of the mission as a whole.

Beyond 1995 *Ulysses* will also form an important complement to ESA's Solar Heliospheric Observatory (SOHO), and NASA's WIND mission. These spacecraft, from positions close to the Earth, will study the Sun, monitor the solar wind, the heliospheric magnetic field, and energetic particles.

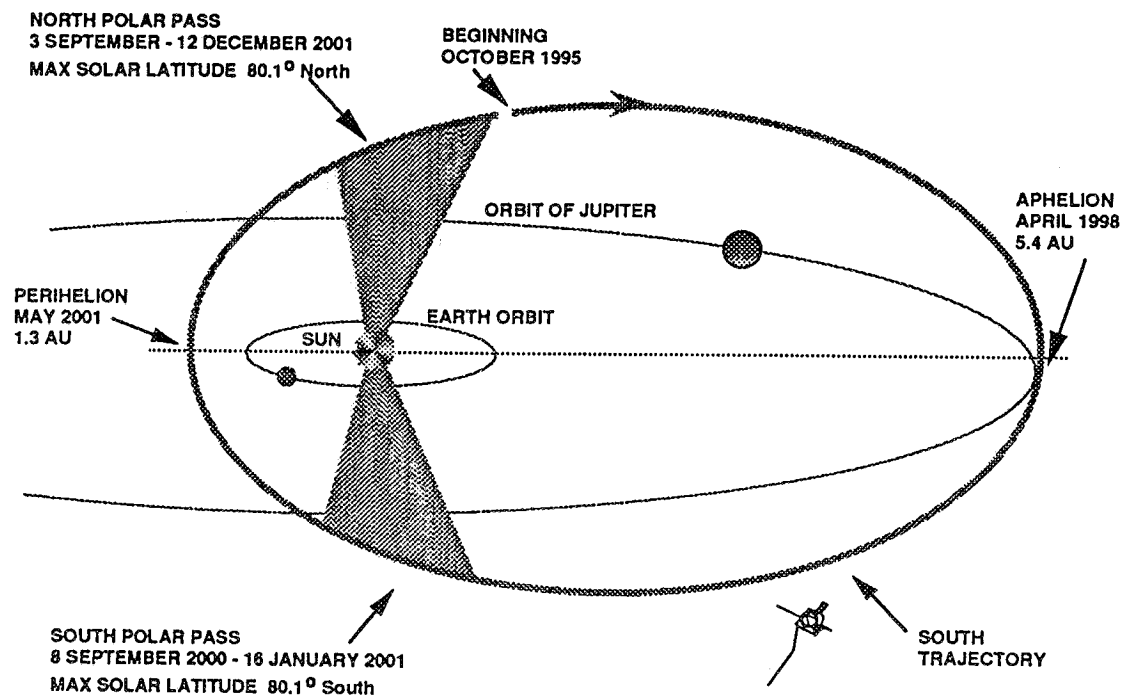
Current Status

Both scientific^{6,7,8} and engineering^{9,10} reports on the status of the *Ulysses* mission have been given periodically in the past. The first four years of the mission have not been trouble free, but there has been no malfunction or degradation that seriously threatens the viability of a second solar orbit. Mission operations have proceeded well, as evidenced by the near continuous flow of science data since launch, and with a few exceptions the spacecraft has performed nominally.

In November 1990, shortly after launch, the

spacecraft body are subjected to the same motion of their fields of view.

The reason for the nutation has been established¹¹ as thermal bending of the axial boom causing torque reactions on the central body, complicated by a severe underperformance of the spacecraft's passive nutation dampers. Fortunately, thermally-induced nutation can only occur under certain conditions of solar distance and Solar Aspect angle, which are not met for long phases of the mission. More importantly, the spacecraft's on-board conical scanning control mode (CONSCAN) has been used successfully to control nutation instability on several



spacecraft started to nutate immediately after the deployment of the spacecraft's axial boom. Nutation causes the spacecraft spin axis to describe a rosette-like pattern, rather than staying fixed in one direction. Over a period of weeks, this nutation built up to 6.5°, and eventually disappeared on 18 December 1990. Nutation represented a danger to the spacecraft as the flexing motion caused at the root of the axial boom could cause the boom to collapse and damage the spacecraft. The motion also causes the High Gain Antenna (HGA) to depoint, eventually resulting in loss of telemetry as the link margin decreases. Instrument pointing is also effected, as instruments mounted rigidly to the

occasions, and although the threat of nutation must be taken seriously, it no longer compromises the viability of the mission. In March 1992, following *Ulysses* flyby of Jupiter, the spacecraft's redundant systems were checked out. The second Central Terminal Unit (CTU2), a major component of the on-board computer, was found to be malfunctioning. Two bits in a register used for telemetry formatting became linked by a short-circuit, resulting in widespread corruption of data in the telemetry format. Fortunately, CTU1 is still in perfect condition so telemetry formatting during the mission has been and will continue to be uncorrupted. CTU2 will only be used in the event of a malfunction of the

prime unit, and is still perfectly viable as an emergency backup. The corruption produced by the bit linkage is predictable, so the anomaly is by no means catastrophic in terms of data recovery, even if CTU2 had to be used for long periods. Fifty percent of data words are corrupted, and result mainly in increased ambiguity in the science data.

Ulysses' principal emergency mode is termed Disconnection of Non-Essential Loads (DNEL), and consists of the entire payload being switched off followed by a general reconfiguration of the spacecraft platform to redundant systems. At the time of writing, five DNELs have occurred during the mission. These have been attributed to short duration current surges in the Main Switch (which connects the science instruments to the main bus), that occur at the same time as a Reaction Control Subsystem latching valve transition during routine maneuvers. Recovery from DNEL takes 12-48 hours, and the occurrence of DNEL at the current rate is not considered a threat to science continuity. The spacecraft latching valves isolate the propellant tank in the middle of the spacecraft from the thruster clusters. These valves are routinely closed when a maneuver is not taking place, and are closed automatically by on-board logic if significant spin rate or attitude perturbations are detected. In early 1994, new information on the valves' manufacturing history indicated an increased likelihood of failure under certain operating conditions. Maneuver operations were changed so that the number of times the latching valves were cycled was minimized.

Concerns

Despite the demonstrably excellent health of *Ulysses* science instruments and engineering subsystems, continuation of the mission is still dependent on adequate consumables to sustain the spacecraft through another six year orbit. Consumables of concern are power, as supplied by the RTG, and attitude control hydrazine.

Because of launch delays, *Ulysses* beginning-of-mission power was about 287W, and is expected to meet its end-of-northern-polar-pass requirement of 245W. After this, in order to ensure all instruments can be operated throughout the second solar orbit, several modifications will be necessary to the spacecraft operational configuration:

- Hot-redundant units such as the redundant receiver will be powered down when necessary.
- Operations causing power peaks in daily activities, such as attitude manoeuvres, tape recorder operations, commanding, and some instrument reconfigurations will be separated.
- The most power-efficient unit of a redundant pair will always be used.
- At later stages of the mission, thermal safety margins established by the original mission design will be reduced in the light of operational experience of *Ulysses* thermal behavior.

By modifying routine operations as above, it is possible from a power point of view to operate all the science instruments through the second northern polar pass in December 2001.

Apart from power, hydrazine fuel mass remaining is also a potential concern. Fuel is necessary for routine Earth pointing maneuvers, to keep the HGA correctly aligned for telemetry transmission. Fuel may also be required for nutation damping maneuvers, should nutation reoccur in late 1999.

Fuel consumption due to routine attitude maneuvers can be predicted with confidence¹² based on historical performance and knowledge of future mission geometry. Because of the excellent orbit injection accuracy in the early mission, large amounts of the fuel budgeted for trajectory correction maneuvers has not been used. The fuel remaining is ample for routine attitude control and nutation damping, should this become necessary.

Conclusion

The continuation of *Ulysses* observations over a full solar activity cycle are an unparalleled scientific opportunity. The excellent health of the spacecraft instruments and engineering subsystems, coupled with stringent management of consumables, makes a second solar orbit achievable.

Acknowledgments

This paper includes relevant information in the *Ulysses* project contained in project presentations and review material from mission continuation studies. The Author would like to thank colleagues in the *Ulysses* Flight Control Team who are an integral part of mission continuation planning, and for the encouragement and direction received from the Project Science personnel in both Project Offices.

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² *Ulysses: A Journey above the Sun's Poles*. Trans. AGU, 72, 241-248.

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⁵ Mastal, E.F., Campbell, R.W., *RTGs - The Powering of Ulysses*. ESA Bulletin 63, August 1990.

⁶ *The Ulysses Mission: In-Ecliptic Phase*. Geophysical Research Letters, 19, 1235-1314.

⁷ *Ulysses at Jupiter*. Science, 257, 1449-1596.

⁸ *Ulysses Encounter with Jupiter*. J. Geophys. Res., 98, 21, 111-21, 252.

⁹ García-Pérez, R. *Ulysses Log: 1992*, Proceedings of the Second International Symposium on Spacecraft Operations, Pasadena, California, November 1992.

¹⁰ Angold et. al. *Ulysses Operations at Jupiter*. ESA Bulletin 63, August 1990.

¹¹ Crellin, E.B. *Thermo-Elastic Dynamic Instability for Ulysses*. European Space Technology Centre, Working Paper 1637, October 1991, Noordwijk, The Netherlands.

¹² *Extension of the Ulysses Mission*. ESA Science Programme Committee, ESA/SPC(93)25, Paris, 12 May 1993.